

Di-Jet Imbalance Measurements in Central Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR

Kolja Kauder *for the STAR Collaboration*

Wayne State University

Abstract

The STAR collaboration reports the first measurements of the transverse momentum asymmetry A_J of di-jet pairs in central gold-gold collisions and minimum bias proton-proton collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC. We focus on anti- k_T di-jets with a leading jet $p_T > 20$ GeV/c and a subleading jet $p_T > 10$ GeV/c, with a constituent cut of 2 GeV/c, which reduces the effect of the underlying heavy-ion background. We examine the evolution of A_J while reclustering these same di-jets with a lower constituent cut of 200 MeV/c.

For the low p_T constituent cut with a resolution parameter of $R = 0.4$, the balance between the di-jets is restored to the level of p+p collisions which indicates the *lost energy* observed for di-jets with a constituent cut of $p_T^{\text{Cut}} > 2$ GeV/c is recovered. Further variations of R and the constituent p_T -cutoff indicate that the lost energy is redistributed in the form of soft particles, accompanied by a broadening of the jet structure.

Keywords: di-jet imbalance

1. Introduction

The properties of the quark gluon plasma (QGP) formed in high-energy nucleus-nucleus collisions can be studied using highly energetic (hard) partons resulting from hard scatterings in the initial stages of the collision, which fragment and hadronize into collimated cones of particles known as jets. Jets in proton-proton (p+p) collisions at RHIC are well-described by perturbative quantum chromodynamics (pQCD) and can therefore be used as a reference to study medium-induced jet modifications [1]. Advances in jet-finding techniques [2], and the proliferation of high- p_T jets at the higher energies accessible at the Large Hadron Collider (LHC) with a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV, have made it possible to study fully reconstructed jets in heavy-ion collisions. Inclusive jet spectra in the most central Pb+Pb collisions are found to be suppressed when compared to scaled p+p or peripheral Pb+Pb measurements at the same collision energy. The observed suppression is visible for jets with

$p_T \sim 40 - 210$ GeV [3, 4, 5], and for jets reconstructed with a resolution parameter as large as $R=0.5$.

Among the first results of differential jet quenching studies at the LHC was the observation of a striking energy imbalance for highly energetic back-to-back di-jet pairs [6, 4]. This imbalance is defined as $A_J \equiv (p_{T,\text{lead}} - p_{T,\text{sublead}})/(p_{T,\text{lead}} + p_{T,\text{sublead}})$, where $p_{T,\text{lead}}$ and $p_{T,\text{sublead}}$ are the transverse momenta of the leading and sub-leading jet, respectively, and the di-jets are required to be approximately back-to-back. This observable shows a reduced sensitivity to detector effects and the underlying heavy-ion event with respect to inclusive measurements and other di-jet observables. Furthermore, when di-jets with a large energy imbalance were selected at the LHC, it was observed that most of the *lost energy* of these jets seems to be recovered at low momentum and at large angles with respect to the di-jet axis (more than 0.8 sr away) [7, 8]. By contrast, at RHIC energies, recent measurements based on correlations of hadrons with leading reconstructed jets or non-decay (direct) photons [9, 10] indicate that the

lost energy remains much closer to the jet axis. We present the first di-jet imbalance measurement in central Au+Au collisions at RHIC, thus allowing a more direct comparison to jet quenching measurements at the LHC.

2. Analysis Details

The data used in this analysis was collected by the STAR detector in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in 2006 and 2007, respectively. Charged tracks are reconstructed with the Time Projection Chamber (TPC) [11], and the transverse energy (E_T) of neutral hadrons is measured in the Barrel Electromagnetic Calorimeter (BEMC) [12]. To avoid double counting the energy of charged hadrons that leave energy within the BEMC, we employ a so-called full hadronic correction scheme, in which the transverse momentum of any charged track that extrapolates to a tower is subtracted from the transverse energy of that tower. Tower energies are not allowed to become negative via this correction.

Events were selected by an online high tower (HT) trigger, which required $E_T > 5.4$ GeV in at least one BEMC tower. In Au+Au collisions, only the 0-13% most central events are analyzed, where event centrality is a measure of the overlap of the colliding nuclei, determined by the uncorrected charged particle multiplicity in the TPC within $|\eta| < 0.5$. Events are restricted to have a primary vertex position along the beam axis of $|v_z| < 30$ cm. Tracks are required to have at least 20 points measured in the TPC (out of a maximum of 45), a distance of closest approach (DCA) to the collision vertex of less than 1 cm, and pseudorapidity within $|\eta| < 1$.

Jets are reconstructed from charged tracks measured in the TPC and neutral particles in the BEMC, using the anti- k_T algorithm from the FastJet package [2] with resolution parameters $R = 0.4$ and 0.2 . The reconstructed jet axes are required to be within $|\eta| < 1 - R$ to avoid edge effects. In this analysis, the initial definition of the di-jet pair considers only tracks and towers with $p_T^{\text{Cut}} > 2$ GeV/c in the jet reconstruction to minimize the effects of background fluctuations and combinatorial jets, as well as to make it unnecessary to subtract the average background energy from the jets. For a constituent p_T cut of $p_T^{\text{Cut}} > 0.2$ GeV/c the event-by-event average background energy is subtracted utilizing the density ρ , determined as the median of $p_T^{\text{jet,rec}}/A^{\text{jet}}$ of all but the two leading jets, using the k_T algorithm with the same resolution parameter R as in the nominal jet reconstruction. The area A^{jet} of jets is found within the

FastJet package using active ghost particles [2]. For this part of the analysis, the corrected jet $p_T = p_T^{\text{jet,rec}} - \rho A^{\text{jet}}$ will be used.

The di-jet imbalance $|A_J|$ is calculated for the highest and second-highest p_T (leading and sub-leading) jets in Au+Au HT events, provided they are approximately back-to-back ($|\phi_{\text{lead}} - \phi_{\text{sublead}} - \pi| < 0.4$) and fulfill $p_{T,\text{lead}} > 20$ GeV/c and $p_{T,\text{sublead}} > 10$ GeV/c. In order to make meaningful quantitative comparisons between the di-jet imbalance measured in Au+Au to that in p+p, it is necessary to compare jets which have similar initial parton energies in the two collision systems, and to take the remaining effect of background fluctuations into account. Therefore a di-jet imbalance reference data set is constructed in this analysis by embedding p+p HT events into minimum bias Au+Au events in the same centrality class (p+p HT \otimes Au+Au MB). The jet energies are not corrected back to the original parton energies. During embedding, we account for the differences between Au+Au and p+p in tracking efficiency in the TPC ($90\% \pm 7\%$), relative tower efficiency ($98\% \pm 2\%$, negligible), and the relative tower energy scale ($100\% \pm 2\%$). Systematic uncertainty on $|A_J|$ was assessed in this process by varying the relative efficiency and tower scale within their uncertainties and is shown in the p+p HT \otimes Au+Au MB embedding reference as colored shaded boxes.

3. Results

In Fig. 1 the $|A_J|$ distribution from central Au+Au collisions for anti- k_T jets with $R = 0.4$ (solid red markers) is compared to the p+p HT embedding reference (p+p HT \otimes Au+Au MB, open red markers) for a jet constituent p_T -cut of $p_T^{\text{Cut}} > 2$ GeV/c. Di-jets in central Au+Au collisions are significantly more imbalanced than the corresponding p+p di-jets. To quantify this difference, the p-value for the hypothesis that the two histograms represent identical distributions was calculated via a χ^2 -test [13] including only the statistical uncertainties. We find a p-value below 10^{-4} , affirming the hypothesis that the Au+Au and p+p HT \otimes Au+Au data are not drawn from the same parent A_J distributions.

In order to assess if the di-jet imbalance can be restored by including the jet constituents below 2 GeV/c in transverse momentum, the jet-finder was run again on the same events but lowering the constituent p_T -cut to $p_T^{\text{Cut}} > 0.2$ GeV/c. The absolute di-jet imbalance $|A_J|$ was then recalculated for low constituent p_T di-jet pairs that could be geometrically matched to the initial di-jet pairs reconstructed with $p_T^{\text{Cut}} > 2$ GeV/c.

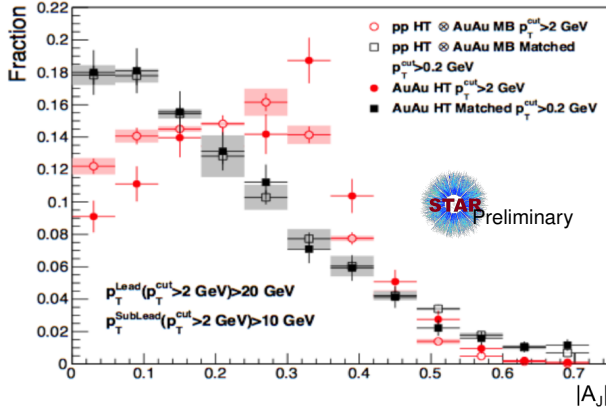


Figure 1: (Color online.) Normalized $|A_J|$ distributions for Au+Au HT data (filled symbols) and p+p HT \otimes Au+Au MB (open symbols). The red data points are for jets found using only constituents with $p_T^{\text{Cut}} > 2$ GeV/c and the black ones for matched jets found using constituents with $p_T^{\text{Cut}} > 0.2$ GeV/c. In all cases $R=0.4$.

Di-jet pairs were considered matched if their axes were within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < R$. The geometric match is the only requirement, no p_T or other constraints were enforced. The absolute di-jet imbalance $|A_J|$ for these matched low constituent p_T di-jet pairs was recalculated, using background-corrected jet p_T . The reference p+p HT \otimes Au+Au MB embedding distribution was also recalculated to account for the effect of the increased background fluctuations resulting from this low constituent p_T -cut.

In Fig. 1 the matched di-jet imbalance measured for a low constituent p_T -cut in central Au+Au collisions (solid black markers) is compared to the p+p HT \otimes Au+Au MB embedding reference (open black markers). The $|A_J|$ distribution in Au+Au is comparable to the p+p data within uncertainties (the p-value between these two distributions is 0.8), suggesting that the jet energy balance can be restored to the level of p+p in central Au+Au HT events including low p_T constituents and with an anti- k_T jet of resolution parameter $R = 0.4$.

The increase in background fluctuations for the low constituent p_T -cut could lead to an artificial di-jet energy balance unrelated to potential modifications of the jet fragmentation. To estimate the magnitude of this effect, we employed the two different *null hypothesis* procedures. First, we embedded the Au+Au HT di-jets, reconstructed with a constituent p_T -cut $p_T^{\text{Cut}} > 2$ GeV/c, (closed red markers in Fig. 1) into Au+Au MB events with a low constituent p_T -cut and re-calculated $|A_J|$. This procedure explicitly disallows for any balance restoration via correlated signal jet constituents since

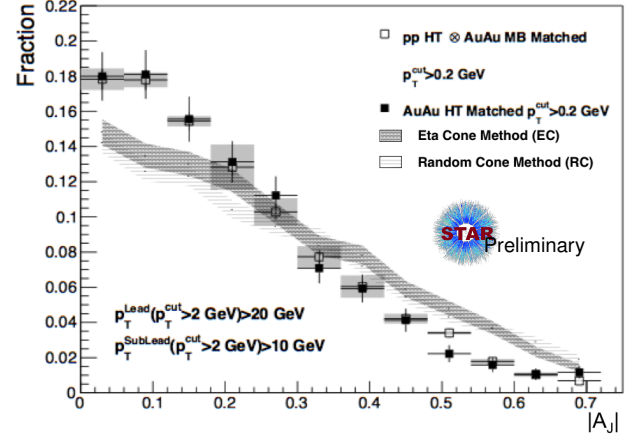


Figure 2: (Color online.) Normalized $|A_J|$ distributions for Au+Au data (filled symbols) and p+p HT \otimes Au+Au MB (open symbols) for di-jets found using constituents with $p_T^{\text{Cut}} > 0.2$ GeV/c and matched to di-jets found with $p_T^{\text{Cut}} > 2$ GeV/c. $R=0.4$. The bands indicate the $|A_J|$ distributions calculated assuming the RC and EC null hypotheses respectively; see the text for details.

the jet is embedded into a different random event. We refer to this as the Random Cone (RC) technique. In the second method, in order to account for potential non-jet correlations within the event, we embed the same di-jet pairs as in the RC method into a different Au+Au HT event with a found di-jet pair, at the same azimuth position but randomly offset in pseudorapidity by at least $2 \times R$. This Eta Cone method (EC) preserves potential background effects due to azimuthal correlations of the underlying event with the di-jet while also excluding any potential jet-like correlation below 2 GeV/c. Both of these methods are shown in Fig. 2 and are compared to the measured matched $|A_J|$ distribution with a low constituent p_T -cut. We conclude that background fluctuations alone can not account for the observed rebalancing, confirming that the energy restored via low p_T constituents is correlated with the jets' fragmentation.

For more differential insight into the energy loss structure, we repeat the second part of the measurement with two variations. First, the p_T^{Cut} for constituents is again lowered to 0.2 GeV/c, but this time the jet resolution parameter R is changed to 0.2. Then we return to $R = 0.4$ but now choose an intermediate p_T^{Cut} of 1.0 GeV/c. Since the jet definition is changed, the embedded p+p reference is recalculated as well. In both cases, the geometrical match to the same original hard-core di-jets with $R = 0.4$ and $p_T^{\text{Cut}} > 2$ GeV/c is retained.

As seen in Figure 3, narrowing the cone to $R = 0.2$ leads to significant differences between central Au+Au and embedded p+p, even when including soft con-

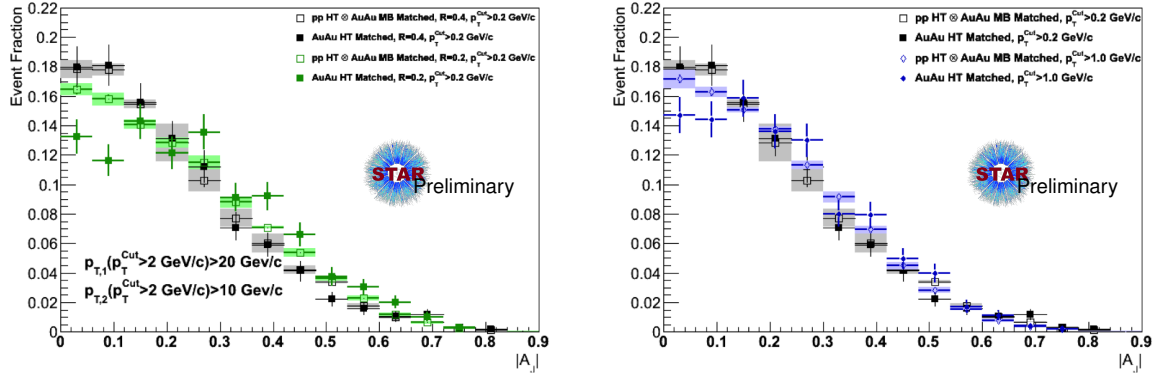


Figure 3: (Color online.) Normalized $|A_J|$ distributions with variations of jet-finding parameters for the matched jets. Left: Green squares show $R = 0.2$ and $p_T^{\text{Cut}} > 0.2$ GeV/c for the matched jets. Right: Blue diamonds show $R = 0.4$ and $p_T^{\text{Cut}} > 1.0$ GeV/c. The original distribution for $R = 0.4$ and $p_T^{\text{Cut}} > 0.2$ GeV/c is shown in black for comparison.

stituents down to 0.2 GeV/c ($p\text{-value} \equiv 2 \times 10^{-4}$). This indicates broadening of the jet structure; jet energy, while contained within the original $R = 0.4$ radius, is nevertheless transported away from the jet axis. The difference between p+p and Au+Au for constituents above 1.0 GeV/c and $R = 0.4$ indicates softening of the constituent spectrum in the medium, albeit not quite as significant, with a $p\text{-value}$ around 5%.

4. Conclusion

In conclusion, these results indicate that even for a biased selection of di-jet pairs with hard cores (constituents above 2 GeV/c), we observe some energy loss to the medium. This lost energy seems to re-emerge as soft particles (below 2 GeV/c) within jets reconstructed with a resolution parameter of $R = 0.4$, but with a broadened jet profile. These findings indicate significant differences when compared to measurements at the LHC [7, 8], in which the balance could only be restored when including constituents at large angles with respect to the di-jet axis.

Since our initial di-jet selection at RHIC contains a significant bias (constituents above 2 GeV/c), it is conceivable that our kinematic selection leads to a pronounced surface bias of the di-jet creation point [14, 15], and subsequently a shorter but finite in-medium path-length with respect to the unbiased di-jet selection at LHC energies. For future measurements with recently collected high-statistics data sets at STAR, this scenario holds the tantalizing promise of *jet geometry engineering* of jet production points, path lengths and interaction probability within the colored medium via variation of the jet-finding parameters and kinematic cuts.

References

- [1] B. Abelev et al. (STAR Collaboration), Phys.Rev.Lett. **99**, 142003 (2007), 0705.4629
- [2] M. Cacciari et al., JHEP **04**, 005 (2008)
- [3] J. Adam et al. (ALICE), Phys. Lett. **B746**, 1 (2015), 1502.01689
- [4] S. Chatrchyan et al. (CMS), PRC **84**, 024906 (2011)
- [5] G. Aad et al. (ATLAS), Phys. Lett. **B719**, 220 (2013), 1208.1967
- [6] G. Aad et al. (ATLAS), PRL **105**, 252303 (2010)
- [7] S. Chatrchyan et al. (CMS), Phys. Lett. **B712**, 176 (2012), 1202.5022
- [8] G. Aad et al. (ATLAS), PLB **719**, 220 (2013)
- [9] L. Adamczyk et al. (STAR Collaboration), PRL **112**, 122301 (2014)
- [10] A. Adare et al. (PHENIX), PRL **111**, 032301 (2013)
- [11] M. Anderson et al., Nucl. Instrum. Meth. A **499**(2-3), 659 (2003), ISSN 01689002
- [12] M. Beddo et al. (STAR), Nucl. Instrum. Meth. A **499**, 725 (2003)
- [13] N.D. Gagunashvili, ArXiv Physics e-prints (2006), physics/0605123
- [14] T. Renk, Phys. Rev. **C87**(2), 024905 (2013), 1210.1330
- [15] T. Renk, Phys. Rev. **C85**, 064908 (2012), 1202.4579